"Phasor assisted Power System Voltage Stability Monitoring and Enhancement Using FACTS"

A synopsis submitted for partial fulfillment of the requirement for the degree of

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BY

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1.1 Introduction

Power systems around the world are undergoing a significant transformation known as “The Energy Transition”. This transition refers to two major changes: the growing incorporation of renewable energy sources and the increasing use of electric vehicles [1][2]. Out of all renewable resources, solar and wind power are growing at the fastest rate. However, as these energy sources are highly varying in nature, they raise concerns about the stability of existing power grids [3].

India, which is the world's third-largest producer of renewable energy and the third-largest consumer of electricity, has installed 40% of its energy capacity in 2022 (160 GW of 400 GW) from renewable sources. Furthermore, the transportation sector accounts for 18% of India's total energy consumption [4]. The increasing pressure on power grids and voltage instability has resulted in widespread power outages throughout the world.

According to the research firm, major power outages impacted at least 350 million people — more than 4% of the global population.

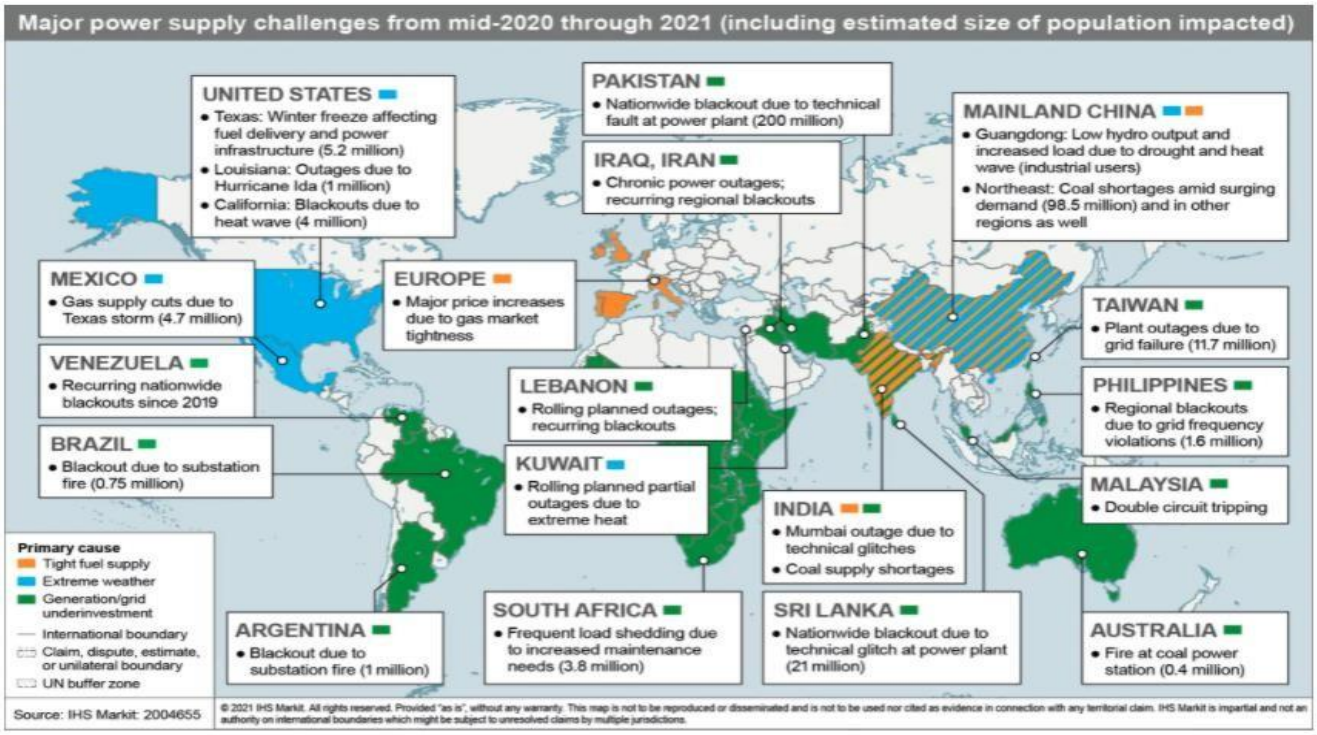
Major power supply challenges from mid-2020 through 2021 (including estimated size of population impacted)
UNITED STATES
• Texas: Winter freeze affecting fuel delivery and power infrastructure (5.2 million)
• Louisiana: Outages due to Hurricane Ida (1 million)
• California: Blackouts due to heat wave (4 million)
PAKISTAN
• Nationwide blackout due to technical fault at power plant (200 million)
IRAQ, IRAN
• Chronic power outages; recurring regional blackouts
MAINLAND CHINA
• Guangdong: Low hydro output and increased load due to drought and heat wave (industrial users)
• Northeast: Coal shortages amid surging demand (98.5 million) and in other regions as well
MEXICO
• Gas supply cuts due to Texas storm (4.7 million)
EUROPE
• Major price increases due to gas market tightness
TAIWAN
• Plant outages due to grid failure (11.7 million)
VENEZUELA
• Recurring nationwide blackouts since 2019
LEBANON
• Rolling planned outages; recurring blackouts
PHILIPPINES
• Regional blackouts due to grid frequency violations (1.6 million)
BRAZIL
• Blackout due to substation fire (0.75 million)
KUWAIT
• Rolling planned partial outages due to extreme heat
MALAYSIA
• Double circuit tripping
INDIA
• Mumbai outage due to technical glitches
• Coal supply shortages
Primary cause
Tight fuel supply
Extreme weather
Generation/grid underinvestment
International boundary
Claim, dispute, estimate, or unilateral boundary
UN buffer zone
ARGENTINA
• Blackout due to substation fire (1 million)
SOUTH AFRICA
• Frequent load shedding due to increased maintenance needs (3.8 million)
SRI LANKA
• Nationwide blackout due to technical glitch at power plant (21 million)
AUSTRALIA
• Fire at coal power station (0.4 million)
Source: IHS Markit: 2004655
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Fig 1.1 Power outages all over world

The most common causes for power outages are high energy demand, maloperation of protective devices, severe weather, equipment failure, high energy demand cyber-attacks etc. [5][4][6][7]. Hence analysis and monitoring of the state of the power system is essential for maintaining its reliability and security.

Traditionally, ‘Supervisory Control and Data Acquisition’ (SCADA) s are being utilized for the monitoring of the PS [8], but there are quite a few limitations of SCADA system such as it measures only magnitude

of voltage and current with very low sampling rate, no time synchronization and observe only steady state which will overcome in WAMS based PMU.

1.2 Phasor measurement units (PMUs)

PMU stands for Phasor Measurement Unit, which is a device used to measure the electrical phasor quantities of a power system. It is a real-time measurement tool that measures the magnitude, phase angle, and frequency of the electrical signals at variouspoints in the power system. It providesthesemeasurements at very high speeds, typically up to 60 times per second.

The synchronized measurements provided by PMUs are used for a variety of purposes, including 'real-time monitoring' , control, and protection of power systems. They are also used for post-event analysis and to support the development of new power system models and algorithms [9].

PMU are seen as basic components in smart grid due to its ability in direct measurement of steady, dynamic and transient state. PMU enhances the quality of state estimation, the performance of real-time monitoring and control. PMUs are more expensive than the traditional measurement devices, but the advantages of PMUs are much more than its financial drawbacks.

The PMU includes analog inputs, GPS system, phase locked oscillator, A/D converter, anti-aliasing filters, microprocessor, and modem as shown in Fig. 1.2.

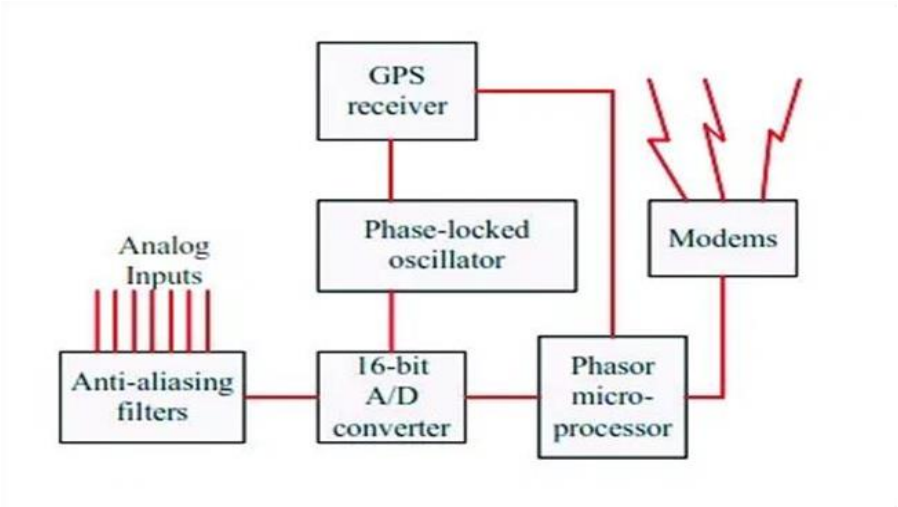

Fig. 1.2 PMU

1.3 APPLICATIONS OF PMU

Data obtained from PMUs are very accurate and with that exact sequence of events that causes blackouts can be analyzed. Therefore, real-time applications of PMU have been popular for the past few years. PMUs placement for different applications is an ongoing process; new methods have been introduced to improve the power system monitoring[10] . PMU applications can be listed as follows:

- 'Real-time monitoring and control'
- Improving PS state estimation
- Post disturbance analysis

- Power system restoration
- Power system protection
- Smart islanding etc.

1.4 Wide area Monitoring System (WAMS)

WAMS is a real-time monitoring system used to continuously monitor and analyze the operation of large-scale power systems, such as interconnected transmission grids or distribution systems. It typically consists of a network of sensors, such as phasor measurement units (PMUs), that are strategically placed throughout the power system to measure voltage, current, and frequency.

The data collected by the sensors are sent to a central control center, where sophisticated analysis software is used to process and visualize the data. The resulting information is used to detect and diagnose power system disturbances, predict system behavior, and aid in the operation and control of the power system.

WAMS plays a vital role in improving the stability and security of the power system and is a key tool in preventing and mitigating blackouts and other power system failures.

The PDC receives phasor data from multiple Phasor Measurement Units (PMUs) and synchronizes the data in real-time to produce a time-aligned output data stream. They can also exchange phasor data with other PDCs located in different areas. PDCs can be categorized based on their role or location. Local PDCs are positioned closer to the PMUs for easier data collection, while Super PDCs operate on a regional scale and handle time-synchronized data from multiple PDCs and several PMUs.

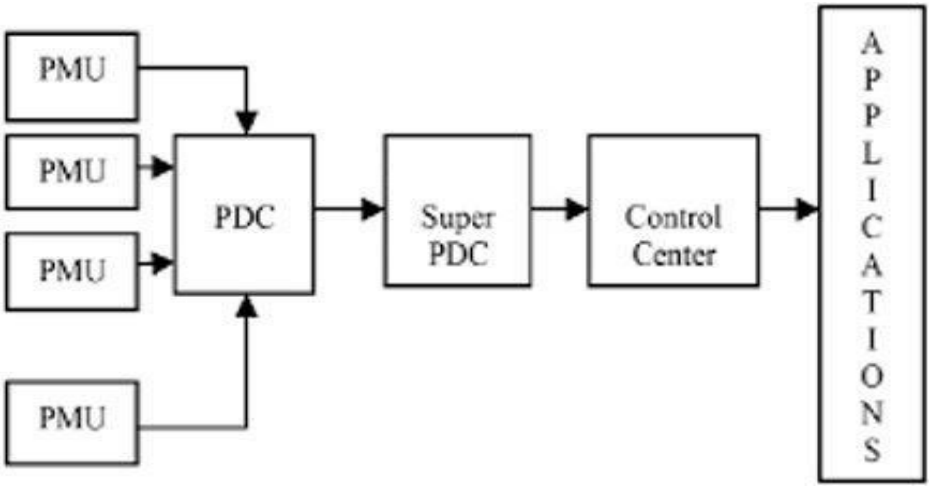

Fig 1.3: Block Diagram of WAMS

This collected data is converted into a time synchronized data set, which can be later used in energy management systems and WAMS using visualization software.

1.5 VOLTAGE STABILITY

"Voltage stability is defined as ability of power system to sustain fixed tolerable voltage at every single bus of the network under standard operating conditions as well as after being subjected to a disruption"

(Kundur). Voltage instability can lead to voltage collapse, which can cause blackouts and damage to power system equipment[11].

Voltage stability can be classified into three categories:

i. **Static voltage stability:** This involves the ability of a power system to maintain voltage levels within acceptable limits during normal and lightly stressed operating conditions.
ii. **Dynamic voltage stability:** This involves the ability of a power system to maintain voltage levels within acceptable limits during system disturbances, such as faults, switching operations, or load changes.
iii. **Transient voltage stability:** This involves the ability of a power system to recover from voltage instability following a major event, such as a fault or loss of generation.

Voltage stability can also be classified based on disturbances over which it is analyzed [12] this context, voltage stability can be classified as:

i. **Small Disturbances:** Small disturbances are typically caused by variations in load demand or changes in system operating conditions. These disturbances are usually transient and do not cause any significant voltage stability issues. Examples of small disturbances include the switching of loads, changes in system topology, and small variations in generation output.
ii. **Large Disturbances:** Large disturbances are typically caused by equipment failures or severe weather conditions. These disturbances can lead to significant voltage instability and can cause voltage collapse. Examples of large disturbances include transmission line or transformer faults, generator outages, and severe weather conditions such as storms or hurricanes.
iii. **Long-duration Disturbances:** Long-duration disturbances are typically caused by changes in system load or generation that persist for an extended period. These disturbances can cause voltage instability and can lead to voltage collapse over time. Examples of long-duration disturbances include changes in system load due to population growth, changes in industrial activity, or changes in the weather.
iv. **Short-duration Disturbances:** Short-duration disturbances are typically caused by sudden changes in system load or generation. These disturbances can cause voltage instability and can lead to voltage collapse if not properly managed. Examples of short-duration disturbances include the sudden loss of a large load or generator, or the sudden restoration of a faulted transmission line.

Each of these categories of voltage stability is important for ensuring the reliable operation of a power system. Voltage stability studies are conducted to identify potential voltage stability problems and to develop mitigation strategies to address them.

1.7 VOLTAGE STABILITY ANALYSIS

Voltage stability analysis is a process that is used to evaluate the ability of an electric power system to maintain a steady voltage level during normal and abnormal operating conditions.

Voltage stability indices are important tools used in power systemanalysis to assess theability of the system to maintain an acceptable voltage level during normal and contingency conditions. These indices are based on local and wide-area measurements and provide useful information for power system operators to take corrective measures before voltage instability occurs [13] [14].

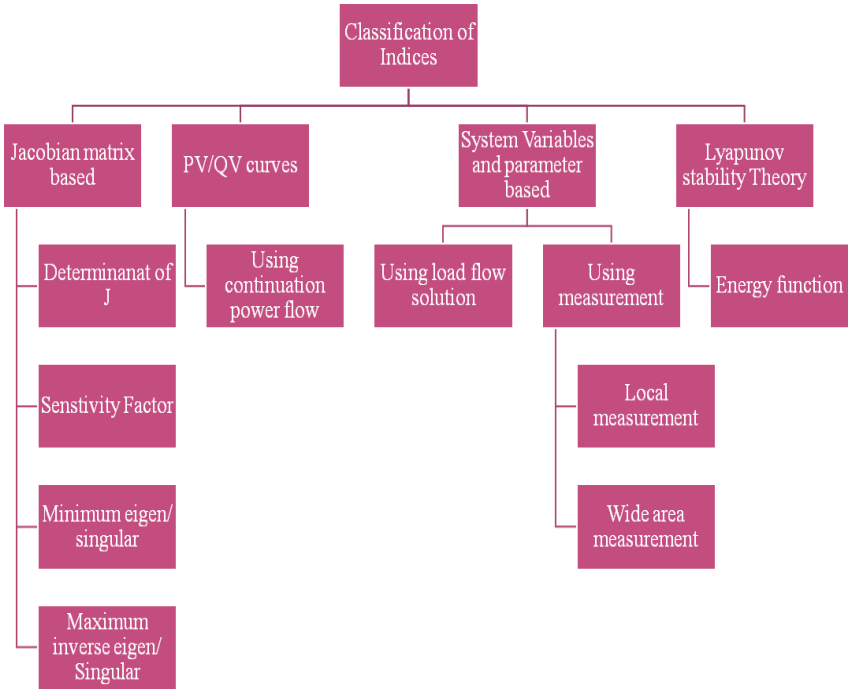

Fig 1.4 Classification of Voltage Indices

1.8 VOLTAGE STABILITY ENHANCEMENT

To maintain the stability of the power system, it is necessary to operate it within a sufficient voltage stability margin. If the system operates with a smaller voltage stability margin, corrective control action must be taken to improve voltage stability. Two different methods can be used for taking control action against voltage instability: preventive and corrective control [15]. Corrective control actions are reactive and are taken in response to a problem that has already occurred, while preventive control actions are proactive and are taken to prevent problems from occurring in the first place.

To enhance voltage and maintain a stable power supply, several **control** actions can be taken. Some of these actions include:

i. **Reactive Power Compensation**: Reactive power compensation can be achieved through the installation of reactive power compensation equipment like capacitors or reactors. These devices help to regulate voltage levels by absorbing or supplying reactive power as needed.
ii. **Load Shedding:** Load shedding involves the intentional reduction of power supply to certain areas to prevent system-wide voltage collapse. It can be automated or manually activated during times of peak demand.
iii. **Voltage Regulation:** Voltage regulation involves the installation of voltage regulators to maintain the voltage levels within an acceptable range. Voltage regulators can be installed at key points within the power system to maintain voltage stability.
iv. **Generator Control**: Generator control involves monitoring and controlling the output of generators to ensure that they are operating within safelimits. This can be achieved using automatic voltage regulators or other control devices.

v. **System Monitoring:** Continuous monitoring of the power system is important to detect any abnormalities in the system and take corrective actions before they become a problem. This can be achieved using automated monitoring systems or through manual monitoring.

vi. **Maintenance and Upgrades**: Regular maintenance and upgrades of the power system equipment are important to ensurethat they areoperating at their optimumcapacity. This can include replacing old or faulty equipment or upgrading to more advanced technology.

Control devices commonly used for Voltage Stability Enhancement (VSE) comprises of:

1. Reactive compensating devices
2. Transformer tap changers
3. Reactive power output of generators

Voltage security is an essential aspect of maintaining a stable and reliable power system. When the voltage levels deviate from their acceptable range, it can lead to power outages, equipment damage, and even complete system failure. To address this issue, power system operators use various methods, such as using FACTS devices based on power electronics technology [16].

FACTS are classified as Series, Shunt, Series-series and shunt series. Some of them are SVC, TCSC, STATCOM, SSSC, UPFC and IPFC. The SVC, TCSC and UPFC are frequently used FACTS devices. Different types of FACTS Controllers have different controlling parameters few of them are:

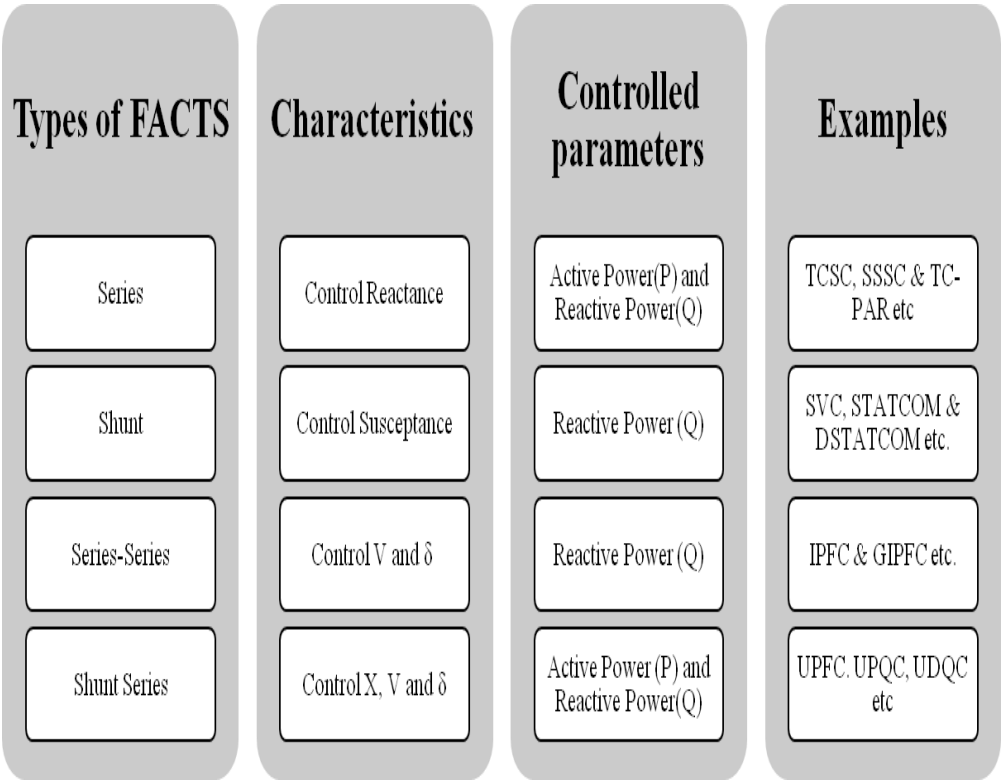

Fig 1.5 Classification of FACTS

1.8 LITERATURE REVIEW:

1. Optimal Placement of PMU

Reference	Method Adopted/ Bus system used	Description/Features	Main Focus	Challenges
[17]	Recursive Tabu Search	Tabu algorithm is used to solve OPP and augmented incident matrix is used to fine system observability with less computational time	Minimize no of PMUs installation to observe complete observability.	Channels capacity not considered
[18]	Modified BPSO/ IEEE 14,30,39,57 and 118	OPP through a amalgam of graph theoretical procedure and BPSO. Initiallythe graph theoretical procedure is used to provide PMU placement which will improve the computation time of Proposed algorithm. Also a new approach of PMU location is purposed.	**OPP with increased computational time**	Computational time is more
[19]	Dual search technique :Simulated annealing and bisecting search algorithm/ IEEE14 bus	In this paper concept of spanning measurement sub graph is introduced. It included the transformation of voltage phasor measurement into pseudo measurement assigned to remote line in the network.	OPP for complete observability	As he guessed the PMU placement so dynamic programming is needed.
[20]	IEEE 298-bus system/ Exhaustive binary search algorithm(EBSA)	Power systems are made topologically observable by placing minimum number of PMU under normal operating condition and single branch outage.	In case of multiple solutions maximum redundancy is considered.	Zero injection bus not considered
[21]	IEEE 14-bus / 30 / 57 118-/New England 39-bus test system/ 2383-bus power system/ Argument Inccidence matrix and Tabu search	TS is executed multiple times and best solution is considered from all previous executions is used.	Solution of OPP with less computational complexity and hence improves robustness of system.	Line outage not considered
[22]	Graph based method / IEEE 14	PMU placement is done based on complete observability with the help of spanning tree.	Depth of un observability	PMU and line out not considered
[23]	Immunity genetic algorithm/ IEEE 14/	It incorporates the immune operator in traditional genetic	With the help of IGA convergence is obtained	Execution time of IGA is more than GA.

	/30 / 57 / 118-bus test systems	algorithm thereby alleviating the degeneration phenomena present in it.	faster than traditional GA algorithm	
[24]	'Non dominated sorting genetic algorithm' /39- and 118-bus IEEE systems	A Pareto-optimal solutions is given which gives solution to OPP with minimizing no of PMU and maximizing measurement redundancy.	The graph theoretical procedure and simple GA are combined in this algorithm to reduce initial no of PMUs candidate location.	Line and pmu outage not considered
[25]	NSDE ('Non dominated sorting differential evolution')	In this combination of pareto non dominated sorting operation and differential evolution algorithm are used to find OPP and maximum measurement redundancy.	OPP with maximum measurement redundancy	Computational time is high for large practical systems and it fails to provide global optimal solution
[26]	ILP / IEEE 14 / New England 39-bus/ NRPG 246-bus Indian system	OPP with critical contingencies and voltage stability based contingency screening method has been employed.	The purposed method has been compared with Depth first search, Direct spanning tree and Direct N-1 spanning tree	Effective in bigger system
[27]	ILP/ IEEE 118/ 'bus observability index' / 'System observability redundancy index'	OPP is carried out in phases. BOI and SORI are considered as indices to rank multiple solutions. BOI gives a measure of number of PMUs and SORI gives sum of all BOI for a system.	OPP done efficiently, improved the computational time and the quality of PMU placement.	Channel limit not considered.
[28]	"A Sequential Quadratic Programming" (SQP) algorithm / IEEE 14	Minimized number and location of PMUs and not considered power flow and injection measurements. Also limited PMU channel capacity is considered. PMUs have limited channels and hence a more accurate PMU placement can be done.	Minimized the total no of PMUs required and maximized measurement redundancy.	Computational time is very large.
[29]	"Binary Integer Linear Programming" (BILP)/ IEEE –7/ 14/ 24/ 30/ 57/ 118-bus systems	Minimized number of PMUs. And branch current phasors.	OPP is done with limited channel capacity.	Only limited PMU channels considered.

2. Wide Area Measurement System (WAMS)

Reference	Description	Focus/ advantage	Future work

[6]	For 'Brazilian Interconnected Power System' model has been established to handle real-time power system monitoring, oscillatory behavior, accident analysis and assess the risk for emergency control. For storage, analysis and display of real time data of power grid PMUs were used.	The dynamic process of power Grid has been enhanced with proper monitoring with the help of PMU.	Method can be utilized for monitoring some other grid.
[30]	A multi-agent system with smart agents: intelligent Agent (IA) and Reactive Agent (RA) in comparison with WAMCS is proposed.	Artificial Intelligent concept.	Real data implementation can be done
[3]	The voltage stability of PS is enhanced with "WAMS based Local Thevenin Index" because of renewable energy integration there is need to examine the effects of the significant penetration of DFIG-based wind farms. A DFIG integrated "16 machine 68 bus" power network has been assessed with LTI from data collected from PMU.	The best location for integrating wind farm into existing power grid has been found considering the voltage stability.	Study can be carried out on other bus systems also and some other Index can be used.
[7]	Various sets of circumstances, limitations, and way out related to load modeling, voltage stability, and islanding protection in real-time are discussed. For execution and research in WAMS some useful software and hardware resources have been examined and presented.	Blackout can be protected by implementing PMUs.	Non availability of failure detection techniques, cyber security and implementation of ML are future research challenges

3. Voltage Stability

Reference	Method/software used	Description	Challenges
[31]	New England 39 / IEEE 118 bus system/MATLAB	With the help of data taken from PMU based on maximum loading capability of bus "Voltage stability index" (VSI) has been purposed to predict voltage collapse.	Real time implementation
[32]	Matlab/Simulink	Voltage enhancement of micro grid is done by controlling Sensitive load bus(SLB), also a new technique for sharing of harmonic compensation is presented.	Still results are not satisfactory.
[33]	IEEE 57 bus system/ MATLAB	Voltage enhancement of insecure buses of wind generation system is done by conducting reactive power generation. Purposed method is compared with Jacobian matrix, susceptance matrix.	Validity can be improved further.
[34]	IEEE 14/ 57 /118 bus systems/ MATPOWER.	Using the data from PMU a new 'hybrid perturbation analysis based voltage stability monitoring' (HPVSM) has been proposed and with Q limit in VSI real time monitoring is done.	Insufficient certified training data.
[35]	IEEE 14,30,57,118,300 BUS system. / MATLAB	Thevenin equivalent technique and Mobius transformation technique has been purposed for calculating load margin estimation. With the help of PMU data a VSB is calculated which provided real-time visualization of the current voltage stability situation.	Only static voltage stability is evaluated.
[36]	IEEE 30/ Polish 3120 summer system/ MATPOWER	WAMS index is measured for real and reactive sensitivities with the help of STI (Sensitivity Thevenin Index).	As constant load is considered so in future research ZIP and exponential load can be considered.
[37]	IEEE 5 Bus system/MATLAB	weakest load bus (candidate buses) is identified based on reactive and active voltage indices for optimal location of DG.	Both QV and pv sensitivity indices need to be considered for allocation of DG

[38]	IEEE 2 / New England 29 bus system / MATLAB	Different indices such as ISI, VSBLI, TPSI and VIP PTSI and VSI indices have been studied and results implemented on IEEE 2 bus system and new England 29 bus and it has been concluded that PTSI and VSI depend on the loadability and maximum power transfer of the system and remaining indices depend on the voltage at the loading bus.	These indices considered that reactive power is always at source and hence they are not good indicators for voltage stability.

4. Voltage Enhancement Using FACTS

Reference	Software/ Device/bus system	Methodology and Description	Challenges
[39]	Survey of various research papers	Presented various methods adopted by different researchers for voltage stability enhancement.	Voltage enhancement can be done in future with hybrid techniques with multi task objectives.
[40]	MATPOWER and Power World Simulator GSO 1 TCSC/ IEEE 5 and 14 bus system	An efficient indices 'Reactive power loss sensitivity indices' has been purposed for solving line contingencies, power losses reduction and line load ability.	Varying load can be considered for the future.
[41]	GAMS/SVC and TCSC/ IEEE5 and 118 bus system	In the presence of stressed loading condition and for security of system MILP is formulated for 'ACOPF' model with linearized FACTS devices model (i.e., TCSC and SVC models).	DCOPF can also be further solved
[42]	Matlab/ TCSC and TCPS/ IEEE 30 and 57 bus sytem	OKHA is proposed to solve OPF with incorporating facts devices which minimizes the fuel cost, active transmission loss, emission reduction and combined economic and environmental losses.	Computational time is more and less accuracy
[43]	MATLAB/IEEE 30 and 57 bus systems	'Artificial Bee Colony' (ABC) Algorithm has been purposed and applied to solve 'Optimal Reactive Power Dispatch' (ORPD) problem. L-Index is used to find voltage stability.	Computational time is high

1.9 OUTCOMES:

1. Power system monitoring is essential for maintaining reliability and security. This was conventionally done with the help of SCADA based systems. It is observed that data rate of SCADA systems is quite low, and measurement taken by SACDA are not synchronized, also phase angle of Voltages and line currents remain unknown. Due to these drawbacks SCADA is replacedby a PMU based monitoring system. So, PMU is a synchro phasor device used for wide area monitoring.
2. It is not possible to install PMU at every bus because:
    - Its cost is very high.
    - Lack of good communication facilities makes it difficult to install on any bus.

- Also, it is not necessary to install at every node as it measures the volage and current with KVL and KCL.

Hence there is a need to minimize the number of PMUs and to find their Optimal location for maximum redundancy. So, this is done in various studies.

3. There is no unique solution for PMUs placement problem. This is because there are different sets of constraints taken by different researchers according to their objectives for finding solutions with different techniques. Some of constraints are
    - Zero injection buses
    - Depth of unobservability
    - Line outage
    - PMU outage
    - PMU with fixed channels
    - PMU with variable channels
4. The various techniques that are used for finding optimal PMU location can be categorized as follows:
    i. **Meta-Heuristics Techniques**: Tabu search, Graph based method using depth of observability, simulated annealing, Binary Search, BPSO, Genetic Algorithm, Immunity GA, non-dominated solving differential evolution algorithm etc.
    ii. **Deterministic Technique**: 'Integer Linear Programming' , 'Integer Quadratic Programming', Mixed Integer Linear Programming etc.
5. In many approaches, achieving complete observability of the systemwith the least possiblenumber of PMUs is considered the main objective. In some cases, a multi-objective approach is proposed to optimize the placement of PMUs, with the goal of achieving complete systemobservability while also maximizing the measurement redundancy of the buses.
6. Various indices based on actual data collection have emerged to monitor voltage stability, which allow defining operating states, critical network areas, limits and voltage stability margins. Following are the indices opted by researchers to find voltage stability :
    i. Local Voltage Stability Indices: Voltage Collapse Margin (VCM), L-index,Voltage Stability Index (VSI) etc.
    ii. Wide-Area Voltage Stability Indices: Modal Analysis based Indices, Voltage Stability Margin (VSM),Line Outage Distribution Factor (LODF) etc.
7. FACTS is a power electronics-based device that controls the parameters of AC transmission system such as magnitude of voltage, phase angle at selected buses and line impedances of transmission system to regulate active and reactive power flow for improving loading capability of lines, increasing system security.
8. Different voltage analysis techniqueshave been adopted by different researchersto enhancevoltage stability by using different FACTS controllers. [39]. According to reviewed papers Voltage stability techniques can categorized as follows:
    i. Conventional techniques
        a. Static Analysis: Power flow method, Modal analysis, singular value Decomposition method.
        b. Dynamic Analysis: Lyapunov based method, Bifurcation analysis method, time domain Simulation method etc.
    ii. Optimization Techniques
        a. Deterministic Techniques: Linear Programming, Mixed Integer nonlinear programming, Analytical approach, optimal power flow method.

b. Artificial Intelligent Techniques: GA, Symbiotic organism, Search based method, Artificial Bee Colony etc.
c. Hybrid optimization techniques: ABC and ANN, GA and OPF, OPF and SA, PSO and MINLP, OPF and PSO etc.

9. Few researchers have done online monitoring with PMU and voltage enhancement with optimal placement of FACTS[39] [43] [44].
10. A "soft" PMU, also known as a "virtual" PMU, is a software-based implementation of a PMU. Soft PMUs use data from existing sensors in the power system, such as digital protective relays, to estimate the phasor measurements instead of requiring dedicated PMU hardware [45].

1.10 RESEARCH GAP:

1. As per reviewed papers for optimal placement of PMU there are two approaches Meta-heuristic and Deterministic algorithms. The meta-heuristic algorithms do not need a set of constraints to achieve a particular solution, but its computational time is less for large practical systems. Moreover, it fails to provide a global optimal solution in many cases. Deterministic algorithms are usually computationally efficient and can provide a provably optimal solution, but they may have limitations in handling large-scale problems or problems with nonlinear and non-convex constraints.
2. The channel capacity of PMU is limited, but cost varies according to number of channels. As per [46], fixed cost of PMU is ș 20k and every channel costs ș 3k. Only a few researchers have taken this as a constraint.
3. The primary difficulty is to assess transient stability in real-time using highly accurate measurements within a brief timeframe. The absence of an accurate load model is a significant constraint in voltage stability analysis. Furthermore, gathering ‘reactive-power-reserve data’ from the generator bus can be challenging. Poor exploration of voltage sensitivity and inadequate techniques for auto loading reduction present additional obstacles [47][43].
4. The main challenge is to evaluate real-time voltage stability with a precise load model in a short period of time. Therefore, many researchers have purposed load modeling with AI techniques, but ‘insufficient certified training data’ is again a significant limitation [7][34].
5. Furthermore, the PMU data is transmitted to the control center with a delay due to the longer communication time, and the measurement system is limited by the low sampling rate and random detection coordination. As a result, it takes time to obtain a better understanding of the system's behavior based on the PMU data [48]. Due to these reasons, the reduction of time for better visualization is a significant challenge.
6. Most of the research has concentrated on offline estimation of ‘voltage stability margin’. Only a few researchers have focused on online monitoring of ‘voltage stability margin’ and its real time control at regular intervals.
7. Although there are already many monitoring techniques available for voltage enhancement using FACTS, there is still a need for more advanced and effective techniques that can accurately predict the voltage stability margin in real-time [49][50].
8. As PMU is expensive so concept of a "soft" PMU has emerged and only few research have focused on it [45].

1.10 OBJECTIVES:

The objectives of research are:

- To compare various methods of optimal placement of PMUs.
- To implement an appropriate Technique for optimal placement of PMU in the System.

- To analyze and assess the performance of the system for voltage stability.
- To compare various FACTS devices for the application of Voltage Stability Enhancement.
- To enhance voltage stability margin with the help of optimally placed FACTS.

Tentative Methodology to be adopted:

1. PMU placement: CPLEX, MATPOWER, PSAT, GAMS
2. Voltage stability analysis: PSAT, VSAT, Machine Learning, GAMS

Reference

[1] G. Leach, “The energy transition,” *Energy Policy*, vol. 20, no. 2, pp. 116–123, Feb. 1992, doi: 10.1016/0301-4215(92)90105-B.

[2] Y. Strauch, “Beyond the low-carbon niche: Global tipping points in the rise of wind, solar, and electric vehicles to regime scale systems,” *Energy Res Soc Sci*, vol. 62, p. 101364, Apr. 2020, doi: 10.1016/J.ERSS.2019.101364.

[3] R. Chintakindi, P. Pradhan, and A. Mitra, “WAMS based Thevenin Index for voltage stability assessment with increasing wind power penetration and additional distributed load,” *Energy Reports*, vol. 8, pp. 672–683, Apr. 2022, doi: 10.1016/j.egyr.2021.11.215.

[4] “Bureau of Energy Efficiency,” 2022.

[5] “https://www.power-eng.com/policy-regulation/in-2021-at-least-350-million-people-worldwide-experienced-major-power-outages-new-report-says/#gref.”

[6] Xugen Fan, Fei Xiong, and Leihai Jiang, “PMU-WAMS research and application in Brazil,” *Global Energy Interconnection*, vol. 2, no. 1, pp. 085–093, Feb. 2019.

[7] R. Chintakindi and A. Mitra, “WAMS challenges and limitations in load modeling, voltage stability improvement, and controlled island protection—A review,” *Energy Reports*, vol. 8, pp. 699–709, Apr. 2022, doi: 10.1016/j.egyr.2021.11.217.

[8] Dennis J. Gaushell and Henry T. Darlington, “Supervisory Control and Data Acquisition,” in *PROCEEDINGS OF THE IEEE, VOL 75, NO.12, DECEMBER 1987*, Dec. 1987, pp. 1645–1658.

[9] R. B. Bobbo *et al.*, “Enhancing grid measurements,” *IEEE Power and Energy Magazine*, vol. 10, no. 1, pp. 67–73, Jan. 2012, doi: 10.1109/MPE.2011.943133.

[10] H. R. Sudheendra, V. K. Jadoun, N. S. Jayalakskmi, and A. Agarwal, “Latest Trends in PMU Placement Techniques,” in *2020 International Conference on Power Electronics and IoT Applications in Renewable Energy and its Control, PARC 2020*, Feb. 2020, pp. 340–345. doi: 10.1109/PARC49193.2020.236622.

[11] X. Liang, H. Chai, and J. Ravishankar, “Analytical Methods of Voltage Stability in Renewable Dominated Power Systems: A Review,” *Electricity*, vol. 3, no. 1, pp. 75–107, Feb. 2022, doi: 10.3390/electricity3010006.

[12] J. International conference on Mechatronics and automation, *Review Analysis of voltage Stability in Power System*. 2017.

[13] P. Prabhakar, “Voltage stability indices: Formulation and classification perspectives,” *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 12, pp. 5777–5785, Oct. 2019, doi: 10.35940/ijitee.K2188.1081219.

[14] P. Sharma and A. Kumar, “Thevenin’s equivalent based P–Q–V voltage stability region visualization and enhancement with FACTS and HVDC,” *International Journal of Electrical Power & Energy Systems*, vol. 80, pp. 119–127, Sep. 2016, doi: 10.1016/J.IJEPES.2016.01.026.

[15] T. U. Okeke and R. G. Zaher, “Flexible AC Transmission Systems (FACTS),” in *Conference and Exhibition - 2013 International Conference on New Concepts in Smart Cities: Fostering Public and Private Alliances, SmartMILE 2013*, 2013. doi: 10.1109/SmartMILE.2013.6708208.

[16] P. Prabhakar and A. Kumar, “Voltage stability boundary and margin enhancement with FACTS and HVDC,” *International Journal of Electrical Power & Energy Systems*, vol. 82, pp. 429–438, Nov. 2016, doi: 10.1016/J.IJEPES.2016.03.038.

[17] J. Peng, Y. Sun, and H. F. Wang, “Optimal PMU placement for full network observability using Tabu search algorithm,” *International Journal of Electrical Power and Energy Systems*, vol. 28, no. 4, pp. 223–231, May 2006, doi: 10.1016/j.ijepes.2005.05.005.

[18] M. Hajian, A. M. Ranjbar, T. Amraee, and B. Mozafari, “Optimal placement of PMUs to maintain network observability using a modified BPSO algorithm,” *International Journal of Electrical Power and Energy Systems*, vol. 33, no. 1, pp. 28–34, Jan. 2011, doi: 10.1016/j.ijepes.2010.08.007.

[19] T. L. Baldwin, L. Mili, M. B. Boisen, and R. Adapa, “Power System Observability with Minimal Phasor Measurement Placement,” *IEEE Transactions on Power Systems*, vol. 8, no. 2, pp. 707–715, 1993, doi: 10.1109/59.260810.

[20] S. Chakrabarti and E. Kyriakides, “Optimal placement of phasor measurement units for power system observability,” *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1433–1440, 2008, doi: 10.1109/TPWRS.2008.922621.

[21] N. C. Koutsoukis, N. M. Manousakis, P. S. Georgilakis, and G. N. Korres, “Numerical observability method for optimal phasor measurement units placement using recursive tabu search method,” *IET Generation, Transmission and Distribution*, vol. 7, no. 4, pp. 347–356, 2013, doi: 10.1049/iet-gtd.2012.0377.

[22] R. F. Nuqui and A. G. Phadke, “Phasor measurement unit placement techniques for complete and incomplete observability,” *IEEE Transactions on Power Delivery*, vol. 20, no. 4, pp. 2381–2388, Oct. 2005, doi: 10.1109/TPWRD.2005.855457.

[23] F. Aminifar, C. Lucas, A. Khodaei, and M. Fotuhi-Firuzabad, “Optimal placement of phasor measurement units using immunity genetic algorithm,” *IEEE Transactions on Power Delivery*, vol. 24, no. 3, pp. 1014–1020, 2009, doi: 10.1109/TPWRD.2009.2014030.

[24] B. Milošević and M. Begović, “Nondominated sorting genetic algorithm for optimal phasor measurement placement,” *IEEE Transactions on Power Systems*, vol. 18, no. 1, pp. 69–75, 2003, doi: 10.1109/TPWRS.2002.807064.

[25] C. Peng, H. Sun, and J. Guo, “Multi-objective optimal PMU placement using a non-dominated sorting differential evolution algorithm,” *International Journal of Electrical Power and Energy Systems*, vol. 32, no. 8, pp. 886–892, 2010, doi: 10.1016/j.ijepes.2010.01.024.

[26] Sodhi Ranjana, Srivastava S.C, and Singh S.N, “Optimal PMU Placement to Ensure System Observability under Contingencies,” in *IEEE Power & Energy Society. General Meeting (2009 : Calgary, Alta.)*, 2009.

[27] D. Dua, S. Dambhare, R. K. Gajbhiye, and S. A. Soman, “Optimal multistage scheduling of PMU placement: An ILP approach,” *IEEE Transactions on Power Delivery*, vol. 23, no. 4, pp. 1812–1820, 2008, doi: 10.1109/TPWRD.2008.919046.

[28] N. P. Theodorakatos, N. M. Manousakis, and G. N. Korres, “A sequential quadratic programming method for contingency-constrained phasor measurement unit placement,” *International Transactions on Electrical Energy Systems*, vol. 25, no. 12, pp. 3185–3211, Dec. 2015, doi: 10.1002/etep.2027.

[29] V. Rokkamand and R. Bhimasingu, “A novel approach for optimal PMU placement considering channel limit,” in *POWERCON 2014 - 2014 International Conference on Power System Technology: Towards Green, Efficient and Smart Power System, Proceedings*, Dec. 2014, pp. 1164–1171. doi: 10.1109/POWERCON.2014.6993995.

[30] A. Nassaj, “A novel agent-based platform for wide-area monitoring and control in power systems,” in *Advances in Intelligent Systems and Computing*, 2019, vol. 801, pp. 385–387. doi: 10.1007/978-3-319-99608-0_51.

[31] R. Maharjan and S. Kamalasadan, “Voltage Stability Index for Online Voltage Stability Assessment,” in *Proceedings of the 47th Annual North American Power Symposium*, Oct. 2015.

[32] M. Savaghebi, A. Jalilian, J. C. Vasquez, and J. M. Guerrero, “Secondary control for voltage quality enhancement in microgrids,” *IEEE Trans Smart Grid*, vol. 3, no. 4, pp. 1893–1902, 2012, doi: 10.1109/TSG.2012.2205281.

[33] J. H. Liu and J. S. Cheng, “Online Voltage Security Enhancement Using Voltage Sensitivity-Based Coherent Reactive Power Control in Multi-Area Wind Power Generation Systems,” *IEEE Transactions on Power Systems*, vol. 36, no. 3, pp. 2729–2732, May 2021, doi: 10.1109/TPWRS.2021.3053139.

[34] S. M. H. Rizvi, P. Kundu, and A. K. Srivastava, “Hybrid voltage stability and security assessment using synchrophasors with consideration of generator Q-limits,” *IET Generation, Transmission and Distribution*, vol. 14, no. 19, pp. 4042–4051, Oct. 2020, doi: 10.1049/iet-gtd.2020.0201.

[35] H. Y. Su and T. Y. Liu, “A PMU-based method for smart transmission grid voltage security visualization and monitoring,” *Energies (Basel)*, vol. 10, no. 8, Aug. 2017, doi: 10.3390/en10081103.

[36] Reddy Amarsagar and V. Ajjarapu, “Validation of the Sensitivity based Thevenin Index on Large Systems,” in *IEEE Power & Energy Society General Meeting (PESGM)*, 2017.

[37] Nannapaneni Geethika, Medalel Tarek, and Challoo Rajab, “A Comprehensive Analysis of Voltage Stability Indices in the Presence of Distributed Generation,” in *IEEE Conference on Technology for Sustainability*, 2015.

[38] Dennis J. Gaushell and Henry T. Darlington, “Evaluation of indices for voltage stability monitoring using PMU measurements,” *Ingenieria e Investigacion*, vol. 34, no. 3, pp. 44–49, Dec. 2014, doi: 10.15446/ing.investig.v34n3.43002.

[39] Singh Bindeshwar, Singh S.N, Kumar Rajesh, and Tiwari Prabhakar, “A Comprehensive Review on Enhancement of Voltage Stability by using Different FACTS Controllers Planning in Power Systems,” in *International Conference on Electrical, Electronics and Computer Engineering (UPCON)*, 2019.

[40] N. A. Bakar, M. Khairunaz, and M. Desa, “Optimal Placement of TCSC in Transmission Network using Sensitivity Based Method for Multi-objective Optimization,” pp. 201–206, 2017.

[41] A. Nikoobakht, J. Aghaei, M. Parvania, and M. Sahraei-Ardakani, “Contribution of FACTS devices in power systems security using MILP-based OPF,” *IET Generation, Transmission and Distribution*, vol. 12, no. 15, pp. 3744–3755, Aug. 2018, doi: 10.1049/iet-gtd.2018.0376.

[42] A. Mukherjee and V. Mukherjee, “Solution of optimal power flow with FACTS devices using a novel oppositional krill herd algorithm,” *International Journal of Electrical Power and Energy Systems*, vol. 78, pp. 700–714, Jun. 2016, doi: 10.1016/j.ijepes.2015.12.001.

[43] M. Ettappan, V. Vimala, S. Ramesh, and V. T. Kesavan, “Optimal reactive power dispatch for real power loss minimization and voltage stability enhancement using Artificial Bee Colony Algorithm,” *Microprocess Microsyst*, vol. 76, Jul. 2020, doi: 10.1016/j.micpro.2020.103085.

[44] P. Sahu and M. K. Verma, “ONLINE MONITORING OF VOLTAGE STABILITY MARGIN AND ITS CONTROL THROUGH STATCOM,” 2019. [Online]. Available: https://www.researchgate.net/publication/339527210

[45] F. Aminifar, M. Fotuhi-Firuzabad, A. Safdarian, and M. Shahidehpour, “Observability of hybrid AC/DC power systems with variable-cost PMUs,” *IEEE Transactions on Power Delivery*, vol. 29, no. 1, pp. 345–352, 2014, doi: 10.1109/TPWRD.2013.2264022.

[46] Z. Jianjun, S. Dongyu, Z. Dong, and G. Yang, “Load Shedding Control Strategy for Power System Based on the System Frequency and Voltage Stability(Apr 2018).”

[47] H. Li, A. Bose, and V. M. Venkatasubramanian, “Wide-Area Voltage Monitoring and Optimization,” *IEEE Trans Smart Grid*, vol. 7, no. 2, pp. 785–793, Mar. 2016, doi: 10.1109/TSG.2015.2467215.

[48] Prabhakar Priti and Kumar Ashwani, “Performance Evaluation of Voltage Stability Index to Assess Steady State Collapse,” in *6th IEEE Power India International Conference (PIICON)*, 2014.

[49] Prabhakar Priti and Kumar Ashwani, “Voltage Stability Assessment using Phasor Measurement Technology,” in *IEEE 6th India International Conference on Power Electronics (IICPE) 8-10 Dec. 2014, Kurukshetra, India*, 2014.

[50] A. T. Al-Hammouri, L. Nordstrom, M. Chenine, L. Vanfretti, N. Honeth, and R. Leelaruji, “Virtualization of synchronized phasor measurement units within real-time simulators for smart grid applications,” in *IEEE Power and Energy Society General Meeting*, 2012. doi: 10.1109/PESGM.2012.6344949.